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Multi-photon signal in supersymmetry comprising non-pointing photon(s) at the LHC

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We study a distinct supersymmetric signal of multi-photons in association with jets and missing transverse energy. At least one of these photons has the origin in displaced vertex, thus delayed and non-pointing. We consider a supersymmetric scenario in which the gravitino is the lightest supersymmetric particle (LSP) (with a mass $\sim$ 1 keV) and the lightest neutralino is the next-to-lightest supersymmetric particle (NLSP). The NLSP decays dominantly into a photon and a gravitino within the detector with a decay length ranging from $c\tau_{\tilde{\chi}} \sim$ 50-100 cm. In addition, we assume that the second lightest neutralino and the lightest neutralino are nearly degenerate and this leads to a prompt radiative decay of the next-to-lightest neutralino into a photon and a lightest neutralino with a large branching ratio. Such degenerate neutralinos can be realised in various representations of the $SU(5)$, $SO(10)$, and $E(6)$ Grand Unified Theories (GUTs). The non-pointing photons can be reconstructed at the electromagnetic calorimeter of the ATLAS inner-detector, which have been designed with good timing and directional resolution. We find that with a centre-of-mass energy $E_{cm} = 14$ TeV at an integrated luminosity of 100 fb^{-1} one may see evidence of hundreds of tri-photon events and a few four-photons events at the LHC, in addition to several thousands di-photon events. We also predict the event rates even at the early phase of LHC run.

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I. INTRODUCTION

In this era of the Large Hadron Collider (LHC) the TeV scale physics is expected to be probed. Supersymmetric Standard Model (SSM) is one of the most interesting and attractive candidate for physics beyond the Standard Model (SM). It offers a possibility of gauge coupling unification and dark matter candidate, and also solves the gauge hierarchy problem. Once supersymmetry (SUSY) is realized as a local symmetry [1], it predicts the existence of the gravitino $\tilde{G}$ as the spin-3/2 superpartner of the graviton. Supersymmetry breaking leads to a non-zero mass of the gravitino through the super-Higgs mechanism, in which the gravitino "eats up" the spin-1/2 goldstino associated with spontaneously broken local supersymmetry [2–5]. The mass $m_{\tilde{G}}$ of the gravitino is governed by the scale of SUSY breaking and can range from as low as eV scale to as high as 100 TeV scale [6–13]. In this work we choose a phenomenological supersymmetric scenario in which gravitino is the lightest supersymmetric particle (LSP) with a mass $m_{\tilde{G}} \sim 1$ keV and look at the collider signatures of such a scenario at the LHC. Such light gravitinos also have implications in cosmology. First of all, one should note that the dark matter relic density is presently known to be $\Omega_{DM}h^2 \simeq 0.11$ [14]. In addition, constraints on structure formation require that the bulk of the dark matter should be cold or warm [15]. For a gravitino with a mass $m_{\tilde{G}} \sim 1$ keV, nonstandard cosmology and a nonstandard gravitino production mechanism are required to satisfy small-scale-structure constraints and to avoid overclosure [16]. One might also need some other dark matter particle. An example of a nonstandard early-Universe physics is to consider a low-reheating temperature [17, 18]. In Ref.[18] a low-reheat scenario has been proposed in which a gravitino of mass $m_{\tilde{G}} = 1$–15 keV can have the right abundance to be the warm dark matter.

The interactions of the gravitino are suppressed by the reduced Planck Scale $M_P = 2.4 \times 10^{18}$ GeV and a light gravitino interacts more strongly than a heavy gravitino. Light gravitinos are primarily produced at colliders in the decays of the NLSP. In our scenario the lightest neutralino ($\tilde{\chi}_1^0$), which is predominantly a bino, is the NLSP and it decays dominantly into a photon and a gravitino. These photons are delayed and non-pointing as they are not pointing to the interaction vertex where the NLSP is produced. Along with this we also look into the radiative decay of the second-lightest neutralino ($\tilde{\chi}_2^0$) i.e., $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$, where the emitted photons are prompt. Thus our main goal in this paper is to study the spectacular

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multi-photon events at the LHC where there is a mixture of prompt photons and non-pointing photons in the final states. In order to have a large branching ratio of the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$, we choose a framework where the $U(1)$ and $SU(2)$ gaugino soft SUSY breaking mass parameters M_1 and M_2, respectively are very close and result in nearly mass degenerate $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$.

In a minimal supergravity like framework (mSUGRA) the gaugino masses are unified at the high scale (unification scale). When they run down to electroweak symmetry breaking scale (EWSB) the gaugino mass ratio gets modified through renormalisation group effects (RGEs). At the EWSB scale the approximate ratio of the gaugino masses are given as $M_1 : M_2 : M_3 \simeq 1 : 2 : 6$, where M_3 is the $SU(3)$ gaugino soft SUSY breaking mass parameter and M_1, M_2 have been defined in the previous paragraph. So it is very clear from the above ratios that in a mSUGRA scenario it is almost impossible to have nearly degenerate neutralions at the EWSB scale. But if the gauginos masses are non-universal at the high scale with $M_1 > M_2$ then the RGEs compensate for M_2 and one can have nearly degenerate gauginos at the EWSB scale. In this paper we point out a few grand unified gauge symmetry breaking patterns where this feature can be grabbed.

Light gravitino and its collider signatures have been studied extensively in various context [16, 19–44] and mostly in connection with gauge mediated supersymmetry breaking (GMSB) [8–10]. Signatures involving photons are characteristics of scenarios with neutralino-NLSP. In most of the cases studied so far the lightest neutralino is predominantly a bino and the second lightest neutralino is dominated by its wino component with a large mass splitting between them. However, as emphasized earlier, we will consider a scenario where the lightest and the second lightest neutralino are approximately degenerate in mass. This will lead to multi-photon signatures at the LHC for a 1 keV gravitino, where in the final states we can have combinations of prompt and delayed photons. This is a spectacular signal free from Standard Model backgrounds and has not been studied earlier. The signature of two non-pointing photons is very much distinct and clean with a large event rate at the LHC. We discuss the di-, tri-, and four-photon signals at 14 TeV center-of-mass (CM) energy with 100 fb^{-1} integrated luminosity. We find it very hard to get any significant event rates for four photons at 7 TeV CM energy with 3 fb^{-1}, and it is not a surprise. Let us note in passing that triphoton signatures of Randall-Sundrum model have been studied recently in Ref.[45].

We discuss the p_T distributions of multi photons for different suggested benchmark points (BP). We use the decay kinematics of the neutralino with a sufficiently long lifetime. Schematic diagram of a neutralino decaying into a gravitino and a photon in the ATLAS detector is shown [35] in Fig. 1. If the decay length of the $\tilde{\chi}_1^0$ is comparable to the size of the ATLAS inner-detector [35, 46], high-p_T photons could enter the calorimeter at angles (η_γ) deviating significantly from the nominal angle from the interaction point to the calorimeter cell (η_1).

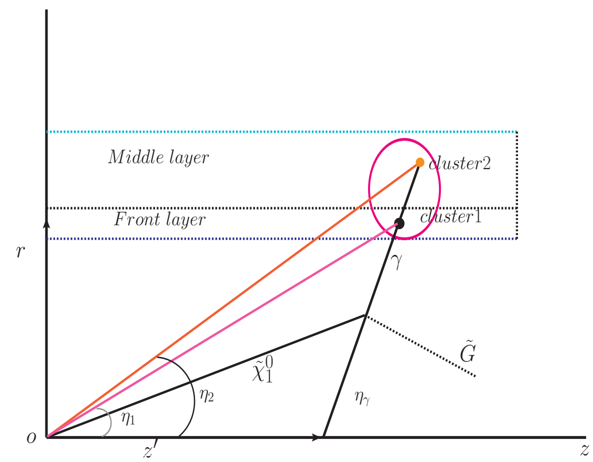

FIG. 1: Decay kinematics of the NLSP (the lightest neutralino) in the ATLAS detector [35, 46].

The plan of the paper is as follows. We discuss the gravitino production from $\tilde{\chi}_1^0$ decay in Sec. II. In Sec. III we discuss how nearly degenerate gaugino masses enhance the branching ratio of the radiative decay of the next-to-lightest neutralino and suggest the possible high scale scenarios from where this degeneracy condition can be achieved. We suggest four benchmark points for our numerical analysis and these are discussed in Sec. IV. In Sec. V we start with our goal for collider simulation and discuss the multi-photons+$jets$ associated with missing transverse energy (MET) as a potential signal at the LHC. Sec. VI contains the results of our numerical analysis and the conclusion is provided in Sec. VII.

II. GRAVITINO PRODUCTION FROM NEUTRALINO DECAY

As discussed earlier, the gravitino gets a mass by the super-Higgs mechanism. The mass of the gravitino is related to the fundamental supersymmetry-breaking scale $\sqrt{F}$, as

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P} \simeq 240 \text{ eV} \left[\frac{\sqrt{F}}{10^3 \text{ TeV}}\right]^2 . \quad (1)$$

The weak-scale gravitino has a very feeble interaction and thus it is usually hard to find its signatures in collider experiments. However, once SUSY is broken spontaneously, the extremely weak gravitino interactions are enhanced at energy scales much larger than the gravitino mass $m_{\tilde{G}}$. This is because in the high energy limit the gravitino has the same interaction as the goldstino and the couplings of the goldstino are proportional to $1/F$ [47–49]. Hence the decays of heavier sparticles to gravitinos are faster for light gravitinos. The partial decay widths of $\tilde{\chi}_1^0$ to $\tilde{G}$

are given as [22, 32, 50]:

$$\Gamma(\tilde{\chi}_1^0 \to \gamma\tilde{G}) = \frac{k_{1\gamma}}{48\pi}\frac{m^5_{\tilde{\chi}_1^0}}{M_P^2 m^2_{\tilde{G}}}; \quad (2)$$

$$\Gamma(\tilde{\chi}_1^0 \to Z\tilde{G}) = \frac{2k_{1Z_T}+k_{1Z_L}}{96\pi}\frac{m^5_{\tilde{\chi}_1^0}}{M_P^2 m^2_{\tilde{G}}}[1-\frac{m_Z^2}{m^2_{\tilde{\chi}_1^0}}]^4; \quad (3)$$

$$\Gamma(\tilde{\chi}_1^0 \to \phi\tilde{G}) = \frac{k_{1\phi}}{96\pi}\frac{m^5_{\tilde{\chi}_1^0}}{M_P^2 m^2_{\tilde{G}}}[1-\frac{m_\phi^2}{m^2_{\tilde{\chi}_1^0}}]^4, \quad (4)$$

where,

$$\begin{aligned} k_{1\gamma} &= |N_{11}\cos\theta_w + N_{12}\sin\theta_w|^2, \\ k_{1Z_T} &= |N_{11}\sin\theta_w + N_{12}\cos\theta_w|^2, \\ k_{1Z_L} &= |N_{13}\cos\theta_\beta - N_{14}\sin\theta_\beta|^2, \\ k_{1h^0} &= |N_{13}\sin\alpha - N_{14}\cos\alpha|^2, \\ k_{1H^0} &= |N_{13}\cos\alpha + N_{14}\sin\alpha|^2, \\ k_{1A^0} &= |N_{13}\sin\beta + N_{14}\cos\beta|^2. \quad (5)\end{aligned}$$

Here N_{ij} are the neutralino mixing matrices, θ_w is the weak mixing angle, α is the Higgs ($\Phi = h^0, H^0, A^0$) mixing angle and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets H_1 and H_2 in the SSM. From the above expressions it is clear that for a bino-like NLSP $N_{11}\cos\theta_w$ is much larger than $N_{12}\sin\theta_w$. The decay modes into the photon dominates over Z and ϕ channels as the later two have phase-space suppressions. Assuming that the decay widths in Z and ϕ channels are negligible, the decay length of the lightest neutralino is given by

$$c\tau_{\tilde{\chi}} = \frac{1}{k_{1\gamma}}\left(\frac{100\text{ GeV}}{m_{\tilde{\chi}_1^0}}\right)^5\left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4 \times 10^{-2}\text{ cm}. \quad (6)$$

For a pure bino-like lightest neutralino and $m_{\tilde{G}} = 1$ keV, we get a decay length $c\tau_{\tilde{\chi}} \approx 70$ cm.

III. RADIATIVE DECAY OF NEUTRALINO: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$

The radiative decay of second lightest neutralino emanates at the one-loop level and decay width is given as [51]:

$$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma) = \frac{g^2_{\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma}}{8\pi}\frac{(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0})^3}{m^5_{\tilde{\chi}_2^0}}, \quad (7)$$

where $g_{\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma} \propto eg^2/16\pi^2$ is an effective coupling. This radiative decay is enhanced [51, 52] by a kinematic factor when $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are nearly degenerate as in this regime of parameter space three body decays are suppressed by a factor ϵ^5, where $\epsilon = (1 - m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_2^0})$. It is being noted in [52–54] that the decay branching ratio of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ is much larger for large $\tan\beta$ and $\mu > M_1, M_2$ with $|\mu| \sim M_1\tan\beta/2$. In the general MSSM scenario the radiative decay branching ratio can reach nearly 100% [54] for $|M_1|,\ M_2 \lesssim 1000$ GeV, with $|M_1|,\ M_2 < |\mu|$ and $|M_1| \sim M_2$. We have calculated the branching ratio of the radiative decay of the second lightest neutralino using **SDECAY version 1.3b** [55].

A. Radiative decay with non-universal gaugino masses

In [54], the enhancement conditions in the radiative decay branching fractions are justified for the minimal supergravity(mSUGRA) models with non-universal gaugino masses. The part of the N=1 supergravity Lagrangian (the part that contains only the real part of the left-chiral superfields Φ_i) containing the kinetic energy and the mass terms for the gauginos and the gauge bosons can be written as:

$$\begin{aligned} e^{-1}\mathcal{L} &= \\ &- \frac{1}{4}Ref_{\alpha\beta}(\phi)(-1/2\bar{\lambda}^\alpha \not{D}\lambda^\beta) - \frac{1}{4}Ref_{\alpha\beta}(\phi)F^\alpha_{\mu\nu}F^{\beta\mu\nu} \\ &+ \frac{1}{4}e^{-G/2}G^i((G^{-1})^j_i)[\partial f^*_{\alpha\beta}(\phi^*)/\partial\phi^{*j}]\lambda^\alpha\lambda^\beta + h.c \end{aligned} \quad (8)$$

where $G^i = \partial G/\partial\phi_i$ and $(G^{-1})^i_j$ is the inverse matrix of $G^j{}_i \equiv \partial G/\partial\phi^{*i}\partial\phi_j$, λ^α is the gaugino field, and ϕ is the scalar component of the chiral superfield Φ and $F^\alpha_{\mu\nu}$ is the unified gauge kinetic term. The F-component of the symmetry breaking scalar field Φ generates gaugino masses with a consistent SUSY breaking with non-zero vacuum expectation value (vev) of the chosen $\tilde{F}$, where

$$\tilde{F}^j = \frac{1}{2}e^{-G/2}[G^i((G^{-1})^j_i)]. \quad (9)$$

The Φ^j's can be a set of GUT singlet supermultiplets Φ^S, which are part of the hidden sector, or a set of non-singlet ones Φ^N, fields associated with the spontaneous breakdown of the GUT group to $SU(3)\otimes SU(2)\otimes U(1)$. The non-trivial gauge kinetic function $f_{\alpha\beta}(\Phi^j)$ can be expanded in terms of the non-singlet components of the chiral superfields in the following way

$$f_{\alpha\beta}(\Phi^j) = f_0(\Phi^S)\delta_{\alpha\beta} + \sum_N \xi_N(\Phi^s)\frac{\Phi^N{}_{\alpha\beta}}{M_P} + \mathcal{O}(\frac{\Phi^N}{M_P})^2, \quad (10)$$

where f_0 and ξ^N are functions of chiral singlet superfields, essentially determining the strength of the interaction and M_P is the reduced Planck mass= $M_{Pl}/\sqrt{8\pi}$. The contribution to the gauge kinetic function from Φ^N has to come through symmetric products of the adjoint representation of the associated GUT group, since $f_{\alpha\beta}$ has such transformation property for the sake of gauge invariance. The non-universal gaugino masses are calculated for $SU(5)$, $SO(10)$ and $E(6)$ grand unified gauge

Representations	$M_1 : M_2 : M_3$ (at $M_{\rm GUT}$)	$M_1 : M_2 : M_3$ (at M_Z)
$\mathbf{75} \subset SU(5)$ $\mathbf{210,\ 770} \subset SO(10)$	$-5 : 3 : 1$	$-5 : 6 : 6$
$\mathbf{2430} \subset E(6)$	$-\frac{9}{5} : 1 : 1$ $\frac{5}{2} : -\frac{3}{2} : 1$	$-1.8 : 2 : 6$ $2.5 : -3 : 6$

TABLE I: *Ratios of gaugino masses for F-terms in representations of $SU(5)$, $SO(10)$ and $E(6)$ leading to nearly degenerate gauginos at low scale.*

groups in [56]. The results for the ratios of gaugino masses are given in Table I. We have tabulated here only the cases where M_1 and M_2 are nearly degenerate at the EWSB scale with $M_1 < M_2$. This fits in our scenario.

IV. BENCHMARK POINTS

In this section we present four benchmark points (see Table II) we have worked with to demonstrate that the nearly degenerate M_1 and M_2 at the EWSB scale can lead to radiative decay of the second lightest neutralino. In addition to this we have also shown that if one has $M_1 < M_2$ and the gravitino in the bottom of the spectrum, then the lightest neutralino has a sizeable branching fraction to decay into a photon and gravitino. This leads to multi-photon signatures in collider experiment. The spectrum has been generated using the **SuSpect version 2.41** [57] with all the input parameters specified at the electroweak scale. The gravitino mass is taken to be $\sim$ 1 keV which is necessary for the fact that the lightest neutralino decays within the detector with a decay length $c\tau_{\tilde{\chi}_1^0} \sim$ 50–100 cm. The radiative decay of the $\tilde{\chi}_2^0$ and decay of $\tilde{\chi}_1^0$ have been calculated using **SDECAY version 1.3b** [55]. The benchmark points we have worked with are consistent with all the low energy constraints like muon $(g-2)_\mu$, $b \to s\gamma$ and the LEP limit on the lightest Higgs boson mass and other charged particles masses [58, 59].

Throughout all of our benchmark points we have kept the value of $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ nearly the same with different choices of μ, $\tan\beta$, squarks, gluino and slepton masses. The high value of μ is important for enhancement of the radiative decay branching fraction of $\tilde{\chi}_2^0$ into a $\tilde{\chi}_1^0\gamma$ pair. We have worked with $m_{\tilde{g}}$ starting from as low as 413 GeV to 740 GeV. We set $A_t = A_\tau = A_b = A_0 =$ -1000 GeV. The large value of $|A_0|$ is required for obtaining a large radiative decay branching ratio (BR) of $\tilde{\chi}_2^0$. For $A_0=$ 0, the three-body-decay modes of $\tilde{\chi}_2^0$ are dominant and the radiative decay is very much suppressed in our case. We have also noted that the radiative decay branching fraction depends less significantly on the sign of A_0. It is a little less for the positive value of A_0 than the negative one keeping $|A_0|$ same. In Table III we tabulate the decay branching fraction of the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for our choice of input parameters. From this table one can see the effect of μ, $\tan\beta$, squark and slepton masses on the radiative decay of $\tilde{\chi}_2^0$. However, the decay branching fraction of the lightest neutralino is determined once the mass of the gravitino, the lightest neutralino and the neutralino mixing parameters are fixed and does not depend at all on the choices of squarks, gluino and sleptons masses.

	BP-1	**BP-2**	**BP-3**	**BP-4**
$\tan\beta$	40	15	10	15
μ	1500	1500	1500	2500
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	601	601	502	701
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	601	601	502	701
$m_{\tilde{\nu}_{e_L}}, m_{\tilde{\nu}_{\mu_L}}$	597	596	496	697
$m_{\tilde{\nu}_{\tau_L}}$	597	596	496	697
$m_{\tilde{\tau}_1}$	591	567	473	652
$m_{\tilde{\tau}_2}$	611	634	529	747
$m_{\tilde{\chi}_1^0}$	200	199	206	206
$m_{\tilde{\chi}_2^0}$	236	237	236	239
$m_{\tilde{\chi}_1^\pm}$	236	237	236	240
$m_{\tilde{g}}$	413	414	688	739
$m_{\tilde{d}_L}$	613	614	521	728
$m_{\tilde{d}_R}$	611	612	518	727
$m_{\tilde{u}_L}$	609	609	515	724
$m_{\tilde{u}_R}$	610	610	516	725
$m_{\tilde{b}_1}$	599	573	486	680
$m_{\tilde{b}_2}$	626	651	551	771
$m_{\tilde{t}_1}$	366	421	215	422
$m_{\tilde{t}_2}$	735	708	627	434
m_{h^0}	110	118	115	119

TABLE II: *Proposed benchmark points (BP) for the study of radiative decay of $\tilde{\chi}_2^0$ and the NLSP $\tilde{\chi}_1^0$. We have set $A_0 =$ -1000 GeV for the third generation squarks and sleptons and it is zero for the rest. Masses of the particles and μ are given in GeV.*

	BP-1	**BP-2**	**BP-3**	**BP-4**
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$	0.30	0.11	0.26	0.10
$\tilde{\chi}_1^0 \to \gamma\tilde{G}$	0.89	0.89	0.87	0.88

TABLE III: *Branching fractions for the decays $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ and $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ for different benchmark points.*

V. COLLIDER SIMULATION

The $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are produced in cascade decays of squarks and gluinos accompanied by hard jets. In an R-parity conserving scenario the gravitino is produced at the end of each cascade, which goes undetected at the collider detector, leading to large amount of missing transverse energy ($\not{E}_T$) (see, Fig. 2). Thus one can have multi-photon signals in association with hard jets and $\not{E}_T$. The collider simulation has been done with a centre of mass energy E_{cm}=14 TeV, at an integrated luminosity of 100 fb^{-1} using the event generator **PYTHIA 6.4.16** [60]. A simulation for the early LHC run at E_{cm}=7

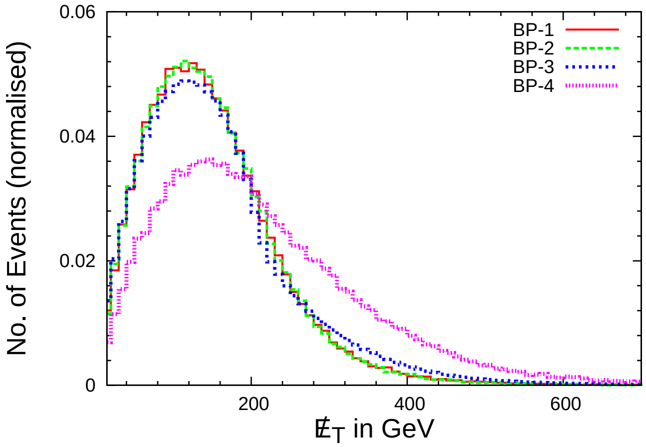

FIG. 2: Missing Energy distribution for different benchmark points with E_{cm}=14 TeV.

TeV and integrated luminosity of 3 fb^{-1} has also been performed. We have used the parton distribution function CTEQ5L [61] with the factorisation (μ_F) and renormalisation (μ_R) scale set at $\mu_R = \mu_F$ =average mass of the final state particles produced in the initial hard scattering. The effects of Initial and Final State Radiation (ISR/FSR) have also been taken into account. Below we mention the numerical values of various parameters used in our calculation [58]
M_Z = 91.187 GeV, M_W = 80.398 GeV, M_t = 172.3 GeV, $\alpha_{em}^{-1}(M_Z)$ = 127.9, $\alpha_s(M_Z)$ = 0.118, where M_Z, M_W and M_t are the masses of the Z-boson, W-boson and top quark, respectively. $\alpha_{em}(M_Z)$ and $\alpha_s(M_Z)$ are the electromagnetic coupling constant and strong coupling constant respectively at the scale of M_Z.

A. Event selection criteria

We have considered the following final states to demonstrate the event rates in multi-photon channels:

- $2\gamma + \not{E}_T + jets$
- $3\gamma + \not{E}_T + jets$
- $4\gamma + \not{E}_T + jets$

where at least one of these photons has the origin in displaced vertex due to the fact that the decay length of the lightest neutralino is $\mathcal{O}$ (50-100 cm). The photon out of a $\tilde{\chi}_2^0$ decay is soft (see Fig. 3-top) while the p_T of the photon coming from a $\tilde{\chi}_1^0$ are normally hard (see Fig. 3-bottom) as the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is $\mathcal{O}$(30 GeV).

The following requirements have been implemented to select isolated photons:

- We have identified photons with p_T more than 30 GeV and $|\eta| \leq$2.5.

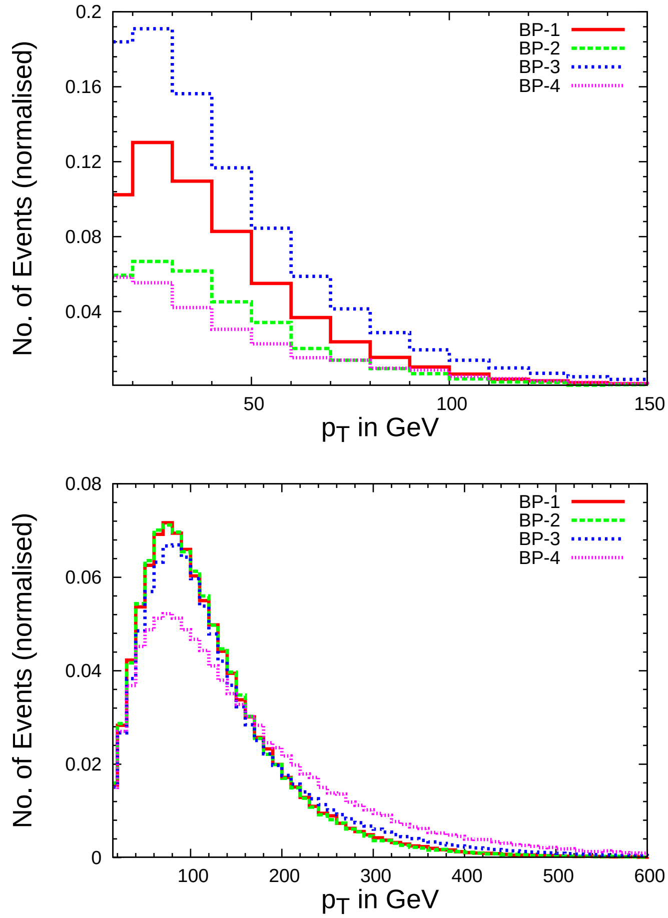

FIG. 3: p_T distributions of the prompt photon (top) and non-pointing photon (bottom) with E_{cm}=14 TeV for all benchmark points.

- A minimum ΔR separation between two photons has been demanded in terms of $\Delta R > 0.2$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.
- A lepton-photon and jet-photon isolation of $\Delta R_{l\gamma} > 0.4$ and $\Delta R_{j\gamma} > 0.6$, respectively have been imposed.
- The sum of hadronic E_T deposit in a cone of $\Delta R =$ 0.2 around the photon is required to be $\Sigma|E_T| <$ 10 GeV.
- To reduce the di-photon background from $\pi^0 \to 2\gamma$ we have also required a photon-photon invariant mass cut $m_\pi - 20$ GeV $< M_{\gamma\gamma} < m_\pi + 20$ GeV.

The photons have been ordered according to their hardness (see Figs. 4, 5 and 6) and a minimum p_T cut has been imposed on each of them depending on the various final states:

- **di-photon**: $p_{T_{\gamma_1}} > 50$ GeV, $p_{T_{\gamma_2}} > 40$ GeV
- **tri-photon**: $p_{T_{\gamma_1}} > 50$ GeV, $p_{T_{\gamma_2}} > 40$ GeV , $p_{T_{\gamma_3}} > 30$ GeV

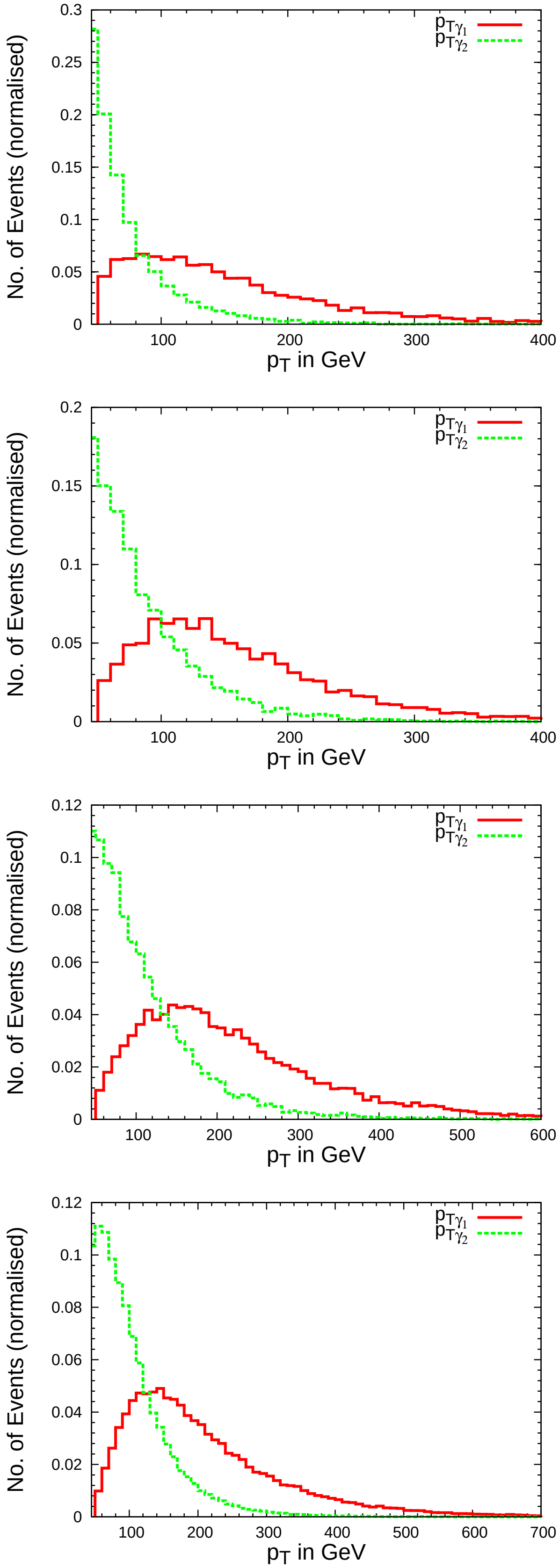

FIG. 4: p_T distributions of di-photons for (from top to bottom) BP-1, BP-2, BP-3, and BP-4 with E_{cm}=14 TeV.

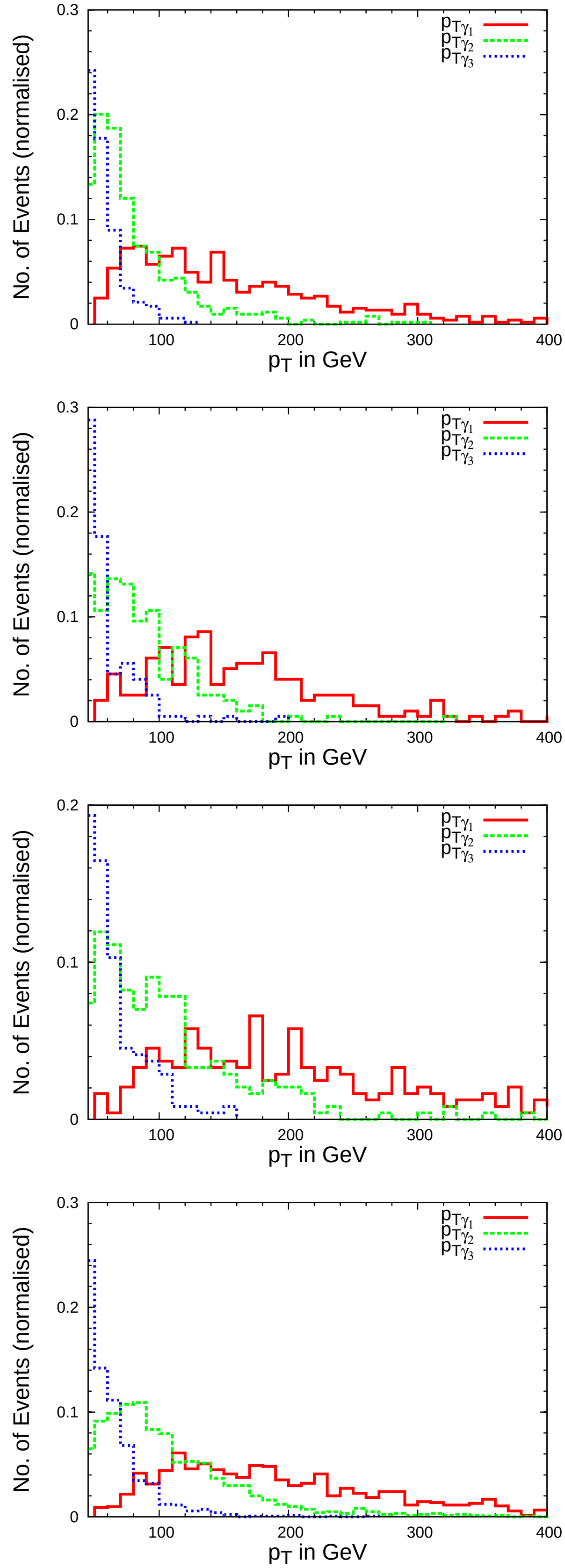

FIG. 5: p_T distributions of tri-photons for (from top to bottom) BP-1, BP-2, BP-3, and BP-4 with E_{cm}=14 TeV.

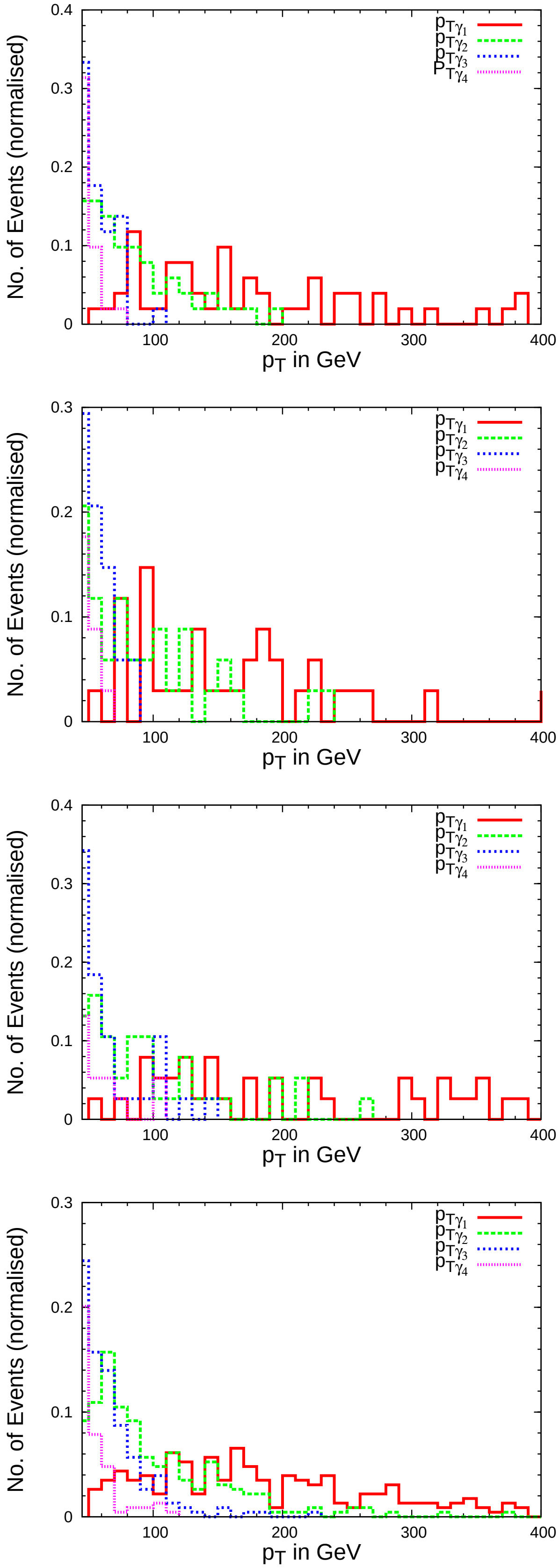

FIG. 6: p_T distributions of four photons for (from top to bottom) BP-1, BP-2, BP-3, and BP-4 with E_{cm}=14 TeV.

- **four-photon**: $p_{T_{\gamma_1}} > 50$ GeV, $p_{T_{\gamma_2}} > 40$ GeV , $p_{T_{\gamma_3}} > 30$ GeV, $p_{T_{\gamma_4}} > 30$ GeV.

We have also incorporated the probability of jet-faking as photon, which is taken to be 0.1% [46, 62] and an identification efficiency of 60% has been used for the non-pointing photons following [46, 63]. We have not taken into account the rapidity dependence of the identification efficiency and used a uniform efficiency for a conservative approach.

VI. RESULTS

In this section we present the numerical results of our simulation. In Table IV we have presented the number of events in the multi-photon channels after applying the basic cuts listed in the previous section. The different benchmark points we have selected correspond to similar $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ with different values of μ, $\tan\beta$, slepton, and squark masses as given in Table II. The radiative decay branching fraction of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ (see Table III) depends on the choice of squarks and slepton masses as well as on the values of $\tan\beta$ and μ, which in turn affect the event rates in various multi-photon channels. In BP-1 the gluino is lighter than the squarks. In this case, $\tilde{\chi}_2^0$ is produced via radiative and three-body decay of gluino which together has a branching fraction of more than 50%. The left-handed squarks decay into a $\tilde{\chi}_2^0 q$-pair either directly (with a branching fraction $\sim$ 8%) or via gluino decay. The right-handed squarks mainly decay into a gluino and a quark pair and the gluino further can decay into a $\tilde{\chi}_2^0 g$ or $\tilde{\chi}_2^0 q\bar{q}$-pair. The situation is similar in BP-2 with only difference is that it has smaller radiative decay branching fraction (11%) of decaying into a $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$-pair due to small $\tan\beta = 10$. In BP-3 the squarks are lighter than the gluino. In this case the gluino directly decays into a $q\tilde{q}$-pair. Therefore the production cross-section of $\tilde{\chi}_2^0$ in SUSY cascade decreases as the dominant contribution in this case comes only from the decay of left-handed squarks with a branching fraction ranging from 30%-35%. The radiative decay branching fraction $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ is slightly greater than BP-2, due to the fact that the squarks and slepton masses are smaller than that in BP-2 (see Table II), which contribute in the loop.

Above all, due to different squarks and gluino masses at different benchmark points the overall SUSY production cross-section changes from one benchmark point to the other. This combined with the different decay branching fractions of $\tilde{q}_L \to \tilde{\chi}_2^0 q$ for various benchmark points, affects the production cross-section of the second lightest neutralino in cascade decay of squarks and gluino and shows up in the final event rates.

From Table IV one can find that in the di-photon channel one has substantial rate at $E_{cm} = 14$ TeV and integrated luminosity of 100 fb^{-1}. The dominant contribution to this channel comes from the two non-pointing photons out of a $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ decay from the two cascades,

SIGNAL	BP-1	BP-2	BP-3	BP-4
$2\gamma + \not{E}_T + jets$	7942	6604	8150	9549
$3\gamma + \not{E}_T + jets$	597	220	165	162
$4\gamma + \not{E}_T + jets$	8	2	3	3

TABLE IV: *Number of signal events, after applying the basic cuts at an integrated luminosity of 100 fb^{-1} and the center of mass energy of 14 TeV for all our benchmark points.*

and constitutes of more than 92% of the total di-photon cross-section. The decay branching fractions of $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ are more than 87% for all of our benchmark points. The next sub-dominant contribution to it comes from one non-pointing photon from $\tilde{\chi}_1^0$ decay and the other prompt photon from radiative decay of $\tilde{\chi}_2^0$. This constitutes $\sim 7\%$ of the total di-photon cross-section. The rest comprises of two prompt photons when we have radiative decay of $\tilde{\chi}_2^0$ from both the cascade or a combination of prompt or non-pointing photon with the ISR/FSR photon, the fraction of which is rather small. We have also presented the di-photon rates even at the early phase of LHC run with $E_{cm} = 7$ TeV at an integrated luminosity of 3 fb^{-1} (see Table V). In BP-1, the di-photon rate is larger than BP-2 with nearly identical spectrum. This attributes to the fact that the radiative decay branching fraction of $\tilde{\chi}_2^0$ at BP-2 is one-third of that in BP-1.

SIGNAL	BP-1	BP-2	BP-3	BP-4
$2\gamma + \not{E}_T + jets$	20	17	19	17
$3\gamma + \not{E}_T + jets$	2	1	0	0

TABLE V: *Number of signal events in the di-photon channel, after applying the basic cuts at an integrated luminosity of 3 fb^{-1} and the center of mass energy of 7 TeV for all our benchmark points.*

The number of events in the tri-photon channel are relatively small since one of these photon comes from radiative decay of $\tilde{\chi}_2^0$. The overall tri-photon event rates are small due to following two reasons: the smaller radiative decay branching fraction of the second lightest neutralino and together with the fact that the photon out of a $\tilde{\chi}_2^0$ decay comes with relatively small p_T (see Fig. 5), because of small mass splitting between $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$. Hence in very small fraction of events they pass the requisite hardness cut. The effect is much more sever in case of four-photon channels as one can see from Table IV. Though we have quoted the event rates also in this case since one hardly has any contamination from the SM backgrounds, one still needs higher luminosity for better statistics.

VII. SUMMARY AND CONCLUSION

We have considered a supersymmetric scenario in which the gravitino (with a mass ~ 1 keV) is the LSP and the NLSP is the lightest neutralino. The second lightest neutralino is nearly degenerate in mass with the lightest neutralino. A possible origin of such a degeneracy at the low-scale lies in the form of non-universal high scale ($\sim 10^{16}$ GeV) inputs of the soft SUSY breaking gaugino mass parameters. We have pointed out that such non-universal high-scale inputs can be realised in various representations of the $SU(5)$, $SO(10)$, and $E(6)$ GUT group.

We have examined the decays of the NLSP and the second lightest neutralino at the LHC. In such a scenario the second lightest neutralino has a substantial branching fraction of decaying into a photon and the lightest neutralino. The branching fraction depends on μ, $\tan\beta$, and other scalar masses in the theory. The lightest neutralino is predominantly a bino and it too decays into a photon and a gravitino with a large branching ratio. Thus one naturally has spectacular multi-photon final states in a collider experiment, where light neutralinos are produced in abundance. The photons out of the NLSP decay are non-pointing and can be identified in the ATLAS inner-detector with an efficiency of 60%. Such non-pointing photons are free from any SM contamination.

We have studied the di-photon, tri-photon, and four-photon final states in association with hard jets and missing transverse energy in the context of LHC both at $E_{cm} = 7$ TeV and 14 TeV and at an integrated luminosity of 3 fb^{-1} and 100 fb^{-1}, respectively. Though the di-photon and tri-photon signals look promising, one needs higher luminosity for the four-photon case.

Detection of such multi-photon final states comprising non-pointing photons at the LHC would have serious implications for early-Universe cosmology and supersymmetry model building. On one hand one needs to have a suitable supersymmetry breaking mediation mechanism, which allows for light gravitino with a mass ~ 1 keV and nearly mass degenerate $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. On the other hand, this may give some hints towards a non-standard cosmological scenario leading to a keV gravitino which is a warm dark matter candidate with right relic abundance.

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